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Tight Focusing of Radially Polarized Pair of Vortices Beam through A Dielectric Interface

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Abstract

Tight focusing properties of radially polarized Gaussian beam with a pair of vortices through dielectric interface is theoretically investigated by vector diffraction theory. For incident beam with a pair of vortices of opposite topological charges, the vortices move toward each other, annihilate and revive in the vicinity of focal plane which results in the generation of many novel focal patterns. The usable focal structures generated through the tight focusing of the double-vortex beams may find applications in micro-particle trapping, manipulation, material processing etc.

Keywords:

1. INTRODUCTION

In researches, the incident light is focused into a uniform medium of refractive index n. However, in many practical applications, an objective is used to focus an incident light beam through an interface between different media of different refractive index. For instance, in the case of laser trapping, a light beam is focused through an interface between glass and water (Ke and Gu, 1998), After that, many researches on the focusing of light beams through dielectric interfaces have been carried out (Biss and Brown, 2001; Wierssma *et al.* 1997; Helseth, 2001; Petrov, 2004; Petrov, 2005). Biss and Brown discussed the focusing of cylindrical vector beams (CVBs) through a dielectric interface (Biss and Brown, 2001). Zhang *et al..*. presented the tight focusing of radially and azimuthally polarized vortex beams through a dielectric interface and a unixial birefringent crystal, respectively (Zhang *et al.* 2008a; Zhang *et al.* 2008b). Moreover, in many practical applications, an objective is used to focus an incident light beam through an interface between different media of different refractive indices. For example, in the application of semiconductor inspection, light beams are focused from air onto silicon substrate. Torok *et al..*. developed the theoretical method for studying the focusing of an electromagnetic wave through dielectric interfaces.(Torok *et al.* 1995a; Torok *et al.* 1995b; Torok *et al.* 1995c). Forits unique properties, tightly focused light beam. For its unique properties, tightly focused light beams have wide potential applications in optical data storage, microscopy, material processing, micro-particle trapping manipulation, etc.(Zhang *et al.* 2008; Ganic *et al.* 2003; Helseth 2000). On the other hand, a great deal of attention has been given to the research of the vortex beam since 1992. The vortex beam, also known as the helical beam, has a continuous spiral phase wave front, which carries an orbital angular momentum (OAM) (Allen *et al.* 1992; Stephen *et al.* 1994). In recent years there has been much research on tight focusing of different kinds of vortex beams, such as linearly polarized, circularly polarized, elliptical polarized vortex beams (Zhang *et al.* 2008; Singh *et al.* 2008; Chen and Pu, 2009). An optical vortex dipole (a pair of vortices with opposite topological charges) propagating in a Gaussian beam may produce a variety of possible trajectories different from that of canonical vortex beams.

2. THEORY

Assume the interface between two dielectric media of refractive indices n1 = 1 and n2 = 3.55, such as focusing in air onto silicon substrate in the application of semiconductor inspection. The geometric focus of the objective without the interface is located at the origin of the coordinate system.

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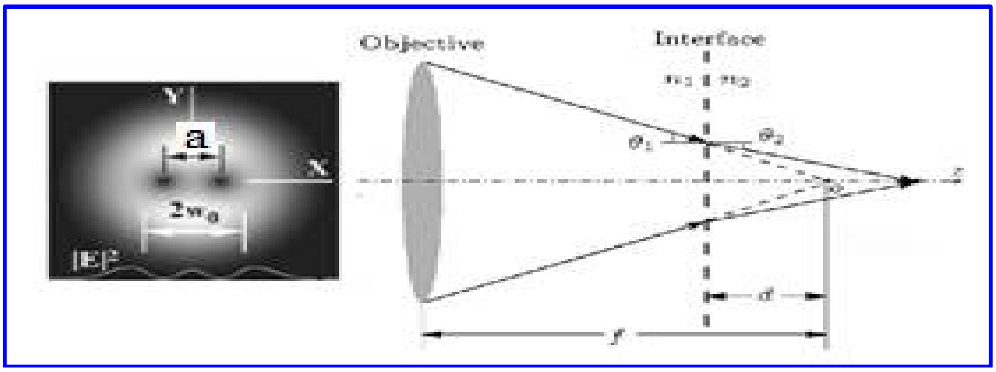

Fig.1: Schematic Diagram for a POV nested in Radially Polarized Gaussian beam focused by a high NA lens.

$$E(r,\psi,z)=\begin{bmatrix}E_x(r,\psi,z)\\E_y(r,\psi,z)\\E_z(r,\psi,z)\end{bmatrix}=\frac{-iE_0}{\pi}\int_0^{\alpha}\int_0^{2\pi}\exp[-ik_0\Phi(\theta_1,\theta_2)]\times\sin\theta_1\sqrt{\cos\theta_1}A(\theta_1) \tag{1}$$

$$\times tp[ik_2 z\cos\theta_2+ik_1 r\sin\theta_1\cos(\psi-\phi)]\times\begin{bmatrix}\cos\theta_2\cos\phi\\\cos\theta_2\sin\phi\\\sin\theta_2\end{bmatrix}d\phi\, d\theta_1$$

Where $k_i= n_i k_0$ is the wave number, $J_n(x)$ is the Bessel function of the first kind of order n, α = arcsin(NA) is the maximal angle determined by the NA of the objective; $t_p$is the amplitude transmission coefficients for parallel polarization states, which is given by the Fresnel equations [16]

$$t_p=\frac{2\sin\theta_2\cos\theta_1}{\sin(\theta_1+\theta_2)\cos(\theta_1-\theta_2)}$$

$$t_s=\frac{2\sin\theta_2\cos\theta_1}{\sin(\theta_1+\theta_2)} \tag{2}$$

The function $\Phi(\theta1, \theta2)$ is given by

$$\Phi(\theta_1,\theta_2)=-d(n_1\cos\theta_1-n_2\cos\theta_2) \tag{3}$$

Representing the so-called aberration function caused by the mismatch of the refractive indices n_1 and n_2. Here θ_1 and θ_2 are related by the well-known Snell law. Here $A(\theta_1)$ describe the pair of vortices. It is considered that two vortices of topological charge m = ±1 locate at $x = \pm a$, embedded in a Gaussian beam, the electric field can be expressed as (Amala Prathiba Janet, 2016; Cheng, 2011).

$$A(\theta_1)=\exp\left(-\frac{r^2}{w^2}\right)\left[r\exp(i\varphi)-a\right]\left[r\exp(-i\varphi)+a\right] \tag{4}$$

w is a constant denoting the beam size, and the distance between the two vortices is decided by a. The two vortices will separate with the increment of a, and two dark cores emerge gradually in the beam. Since the objectives are often designed to obey sine condition, we get $r = f\sin\theta$, where f is the focal length of the high NA objective and θ is the numerical-aperture.

3. RESULTS & DISCUSSIONS

Without loss of generality and validity it is proposed that the parameters are chosen as λ=632.8nm, ω=2mm, f=2mm, NA= 0.9 and m=1. The effect of location of the vortices on the beam pattern in the focal region is shown in Fig 2. It is observed that when a=0, the two vortex of same topological charge, i.e., m=1, overlaps each other and become a Gaussian beam with topological charge m=2. It is observed from Fig. 2(a) the Generated focal segment is a focal hole. Fig. 2(e) shows the intensity plot calculated in the radial direction at the position of maximum intensity and the FWHM of the generated focal hole is measured as 1.12λ. Fig. 2(i) shows the on-axial intensity calculated

atz=4.4λ measures the DOF as 10.2λ. It is observed that by setting a=0.21 w, the weighs of Ex and Ey components are adjusted in such a way that the generated focal spot has a flat top profiled having DOF as 9.7λ and the spot size as 0.92λ and are shown in fig 2(b) ,(f) and (j) respectively. We observed that further increasing a to 0.35w, the Ey component with central minimum get reduced and generated highly confined focal spot having a dominating Ex component. The FWHM of the focal spot is measured as 0.75λ and the focal depths of the focal spot is 8.5λ and are shown in fig (2c),(2g)&(2k) respectively We also noted that further increasing a to 0.8w generated a focal segment bumpy structure of focal depth 6.3 .Since then, the directly transmitted azimuthally polarized component should become much stronger and dominate the total field. Such a transversely polarized focal spot having no longitudinal component is highly useful in applications such as imaging the silicon integrated circuit.

This is because though the radially polarized beam produced sharper focal spot, the strong longitudinal component of the radially polarized beam suffers discontinuity at the interface of two neighboring media and enlarges the focal spot in the high NA medium. Hence beam with strong longitudinal polarization is limited in applications such as silicon integrated circuit (Qin et al 2015). Thus by manipulating the location of the vortices one can tune the focal pattern from a sub wavelength focal hole to a sub wavelength transversely polarized focal spot. This is due to the fact that initially only one dark core is observed in the focal plane when two vortices with opposite topological charges are both located in the center of the incident beam. It then gradually disappeared and formed a sharp focal spot structure as the vortices move away from the center.

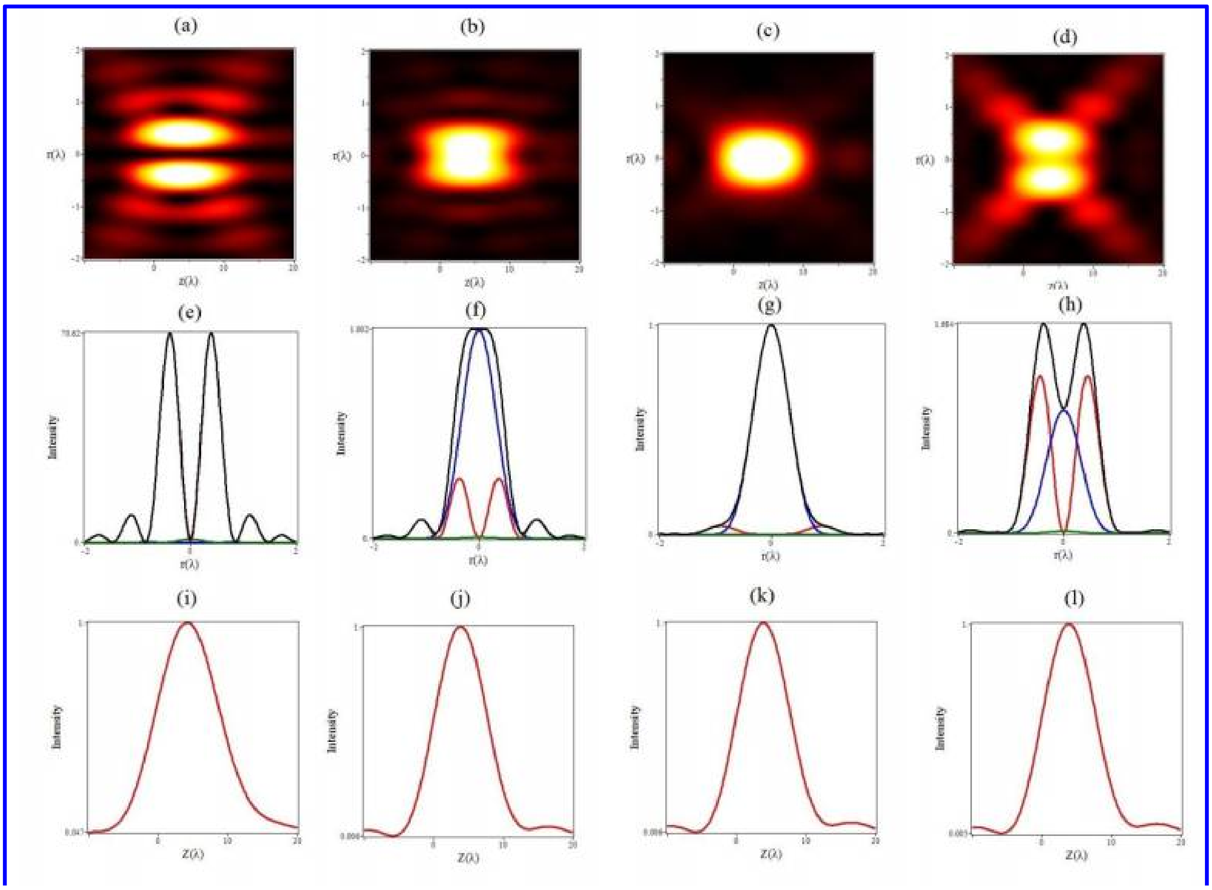

Fig. 2(a-d): shows the 3D intensity distribution in the r-z plane corresponding to a= 0, 0.21w, 0.4w and 0.8w. Fig. 2(e-h): shows the corresponding intensity measured along the radial axis at z=0 and Fig. (i-l) shows the corresponding axial intensity distribution., The other parameters are chosen as λ = 632.8 nm, w =2 mm, f =2 mm, NA= 0.95.

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4. CONCLUSION

The focusing properties of the radially polarized optical vortex dipo le through a dielectric interface is investigated theoretically by vector diffraction theory. It is observed that by properly manipulating the distance between the vortex dipoles one can generate many novel focal patterns such as focal hole, flat top profile and highly confined focal spot suitable for micro particle trapping, manipulation, material processing etc

REFERENCES

Amala Prathiba Janet, C., Udhayakumar, M., Rajesh, K. B., Jaroszewicz, Z. and Pillai, T. V. S., Generating multiple focal structures with high NA parabolic mirror using azimuthally polarized pair of vortices, *Opt. Quantum Electron*., 48, 521-528(2016). doi:10.1007/s11082-016-0790-9

Biss, D. P. and Brown, T. G., Cylindrical vector beam focusing through a dielectric interface, *Opt. Express,* 9(10), 490-497(2001). doi:10.1364/OE.9.000490

Bomzon, Z., Kleiner, V. and Hasman, E., Formation of radially and azimuthally polarized light using space-variant subwavelength metalstripe gratings, *Appl. Phys. Lett*., 79(11), 1587(2001). doi:10.1063/1.1401091

Born, M. and Wolf, E., Electromagnetic theory of propagation interference and diffraction of light, Principles of Optics 7th edn. (Cambridge: Cambridge University Press) 1999.

Chen, Z., Pu, J. X. and Zhao, D. M., Tight focusing properties of linearly polarized Gaussian beam with a pair of vortices, *Phys. Lett.* A 375(32),2958-2963(2011). doi:10.1016/j.physleta.2011.06.035

Chen, B. and Pu, J., Tight focusing of elliptically polarized vortex beams, *Appl. Opt*., 48(7), 1288-1294(2009). doi:10.1364/AO.48.001288

Dai, Ye., Hu, X., Song, J., Yu, B. and Qiu, J., Self-assembled Quasi-periodic voids in glass induced by a tightly focused femtosecond laser, *Chin. Phys.Lett*., 24(7), 19-41(2007). doi:10.1088/0256-307X/24/7/042

Fang, G. J., Tian, B. and Pu, J. X., Focusing properties of the double-vortex beams through a high numerical-aperture objective, *Opt. Laser* Technol., 44(2), 441-445(2012). doi:10.1016/j.optlastec.2011.08.009

Greene, P. L. and Hall, D. G., Focal shift in vector beams, *Opt. Express*., 4(10), 411-419(1999). doi:10.1364/OE.4.000411

Grosjean, T. and Courjon, D., Smallest focal spots, *Opt. Commun*., 272(2), 314-319(2007). doi:10.1016/j.optcom.2006.11.043

Gu, M., Advanced Optical Imaging Theory (Berlin:Springer), Physics, Optics & Lasers, (2007).

Helseth, L. E., Focusing of atoms with strongly confined light potentials, *Opt. Commun*., 212(4-6), 343-352(2002). doi:10.1016/S0030-4018(02)01998-3

Helseth, L. E., Smallest focal hole, *Opt. Commun*., 257(1), 01-08(2006). doi:10.1016/j.optcom.2005.07.019

Indebetouw, G., Optical vortices and their propagation, *J. Mod. Opt*., 40(1), 73(1993). doi:10.1080/09500349314550101

Lerman, G. M. and Levy, U., Tight focusing of spatially variant vector optical fields with elliptical symmetry of linear polarization, *Opt. Lett*., 32(15), 2194-2196(2007). doi:10.1364/OL.32.002194

Molina-Terriza, G., Torner, L., Wright, E. M., García-Ripoll, J. J. and Pérez-García, V. M., Vortex revivals with trapped light, *Opt. Lett*., 26(20), 1601-1603(2001). doi:10.1364/OL.26.001601

Palacios, D. M., Maleev, I. D., Marathay, A. S. and Swartzlander, G. A., Spatial correlation singularity of a vortex field, *Phys. Rev. Lett*., 92 143905(2004). doi:10.1103/PhysRevLett.92.143905

Qin, Y., Zhu, C., Yang, H. and Gong, Q., Supercontinuum generation in atmosphereic-pressure nitrogen using a tightly focused intense femtosecond laser beam, *Chin. Phys. Lett*., 17(6), 413-415(2000). doi:cpl.iphy.ac.cn/Y2000/V17/I6/0413

Rao, L. and Pu, J., Focusing of partially coherent vortex beams by an aperture lens, *Chin. Phys. Lett.*, 24(5), 1252-1255(2007). doi:cpl.iphy.ac.cn/Y2007/V24/I5/01252

Roux, F. S., Canonical vortex dipole dynamics, *J. Opt. Soc. Am. B*, 21(3), 655-663(2004). doi:10.1364/JOSAB.21.000655

Singh, R. K., Senthilkumaran, P. and Singh, K., Tight focusing of vortex beams in presence of primary astigmatism, *J. Opt. Soc. Am. A*, 26(3), 576-588(2009). doi:10.1364/JOSAA.26.000576

Tao, S. H., Yuan, X. C., Lin, J. and Burge, R. E., Residue orbital angular momentum in interference double vortex beams with unequal topological charges, *Opt. Express*, 14(2), 535-541(2006). doi:10.1364/OPEX.14.000535

Torok, P., Varga, P. and Booker, G. R., Electromagnetic diffraction of light focused through a planer interface between materials of mismatched refractive indices: structure of the electromagnetic field. *I, J. Opt. Soc. Am. A*, 12(10), 2136-2144(1995). doi:10.1364/JOSAA.12.002136

Torok, P., Varga, P., Laczik, Z. and Booker, G. R., Electromagnetic diffraction of light focused through a planar interface between materials of mismatched refractive indices: an integral representation, *J. Opt.Soc. Am. A.*, 12(2), 325-332(1995). doi:10.1364/JOSAA.12.000325

Walker, E. P. and Milster, T. D., Proc. *SPIE Int. Soc. Opt. Eng.*, 4443 73(2001).

Youngworth, K. S. and Brown, T. G., Focusing of high numerical aperture cylindrical-vector beams, *Opt. Express*, 7(2), 77-87(2000). doi:10.1364/OE.7.000077

Zhan Qiwen, Properties of circularly polarized vortex beams, *Opt. Lett.*, 31(7), 867-869(2006). doi:10.1364/OL.31.000867

Zhang, Z., Pu, J. X. and Wang, X., Tight focusing of radially and azimuthally polarized vortex beams through a dielectric interface, *Chin. Phys. Lett*., 25(5), 1664-1667(2008). doi: cpl.iphy.ac.cn/Y2008/V25/I5/01664

Zhang, Z., Pu, J. X. and Wang, X., Tightly focusing of linearl polarized vortex beams through a dielectric interface, *Opt. Commun*., 281(13), 3421-3426(2008). doi:10.1016/j.optcom.2008.03.043

Zhang, Z., Pu, J. and Wang, X., Focusing of partially coherent Bessel-Gaussian beams through a high-numerical-aperture objective, *Opt. Lett*., 33(1), 49-51(2008). doi:10.1364/OL.33.000049